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EFFECT OF PRIOR DISTURBANCES ON THE EXTENT AND SEVERITY OF WILDFIRE IN COLORADO SUBALPINE FORESTS

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Abstract. Disturbances are important in creating spatial heterogeneity of vegetation patterns that in turn may affect the spread and severity of subsequent disturbances. Between 1997 and 2002 extensive areas of subalpine forests in northwestern Colorado were affected by a blowdown of trees, bark beetle outbreaks, and salvage logging. Some of these stands were also affected by severe fires in the late 19th century. During a severe drought in 2002, fires affected extensive areas of these subalpine forests. We evaluated and modeled the extent and severity of the 2002 fires in relation to these disturbances that occurred over the five years prior to the fires and in relation to late 19th century stand-replacing fires. Occurrence of disturbances prior to 2002 was reconstructed using a combination of tree-ring methods, aerial photograph interpretation, field surveys, and geographic information systems (GIS). The extent and severity of the 2002 fires were based on the normalized difference burn ratio (NDBR) derived from satellite imagery. GIS and classification trees were used to analyze the effects of prefire conditions on the 2002 fires. Previous disturbance history had a significant influence on the severity of the 2002 fires. Stands that were severely blown down (>66% trees down) in 1997 burned more severely than other stands, and young (~120 year old) postfire stands burned less severely than older stands. In contrast, prefire disturbances were poor predictors of fire extent, except that young (~120 years old) postfire stands were less extensively burned than older stands. Salvage logging and bark beetle outbreaks that followed the 1997 blowdown (within the blowdown as well as in adjacent forest that was not blown down) did not appear to affect fire extent or severity. Conclusions regarding the influence of the beetle outbreaks on fire extent and severity are limited, however, by spatial and temporal limitations associated with aerial detection surveys of beetle activity. Thus, fire extent in these forests is largely independent of prefire disturbance history and vegetation conditions. In contrast, fire severity, even during extreme fire weather and in conjunction with a multiyear drought, is influenced by prefire stand conditions, including the history of previous disturbances.

Key words: Abies lasiocarpa; *blowdown; classification trees; disturbance interactions; fire;* Picea engelmannii; *spruce beetle; subalpine forests.*

Introduction

Disturbances are important in altering stand conditions and in contributing to the spatial heterogeneity of vegetation patterns that in turn may affect subsequent patterns and effects of disturbances (Turner et al. 1989, Wu and Loucks 1995, Mladenoff and Baker 1999, White and Jentsch 2001). Forest stand structures and compositions left by previous disturbances, in conjunction with topographic variation, are believed to be strong determinants of the spread, severity, and ecological effects of subsequent disturbances (Turner et al. 1994, Everham and Brokaw 1996, McCullough et al. 1998). The influence of these factors on the behavior of subsequent disturbances is believed to decrease as the intensity of the latter disturbances increases (Turner et al. 1994, Everham and Brokaw 1996). In the present study, we examined the effect of previous disturbances on the extent and severity of fires in Colorado during the extreme drought of 2002. We focus on the effects of blowdown, bark beetle outbreak, and salvage logging that occurred in the five years prior to the 2002 fires and on the last major stand-replacing fires, which occurred 123 years prior to the 2002 fires.

By creating large loads of dead fuels, blowdowns in many forest types have often been suggested to increase the risk that ignited fires will become extensive or severe (Clapp 1938, Glitzenstein and Harcombe 1988, Putz and Sharitz 1991, Myers and van Lear 1998). Although the amount of dead fuel may greatly increase following a blowdown, there are relatively few documented cases of fires occurring in the years or decades after blowdowns. Furthermore, when post-blowdown fires have been documented, it is not clear if they were attributed to the effects of blowdown or to drought (Wolffsohn 1967). Although for many forest ecosystems there are large uncertainties about the relative importance of blowdown and drought, salvage logging is often implemented after

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blowdown based on the belief that fuel removal is necessary to reduce the risk of large and severe fires (e.g., Elliott et al. 2002; but see Robinson and Zappieri [1999]).

Blowdowns can sometimes trigger outbreaks of insects, particularly of spruce beetles (*Dendroctonus rufipennis* Kirby; Schmid 1981), that can further increase the amount and continuity of fine and coarse dead fuels as a result of tree mortality (Knight 1987). However, the effects of insect outbreaks on flammability are complex and vary with topography, weather, and forest structure (Knight 1987, Stocks 1987, Fleming et al. 2002). There is a scarcity of published work that definitively links the effects of insect outbreaks to increased fire occurrence. For example, despite widespread tree mortality from a severe outbreak of spruce beetle during the 1940s in the Flat Tops area, fires were neither more frequent nor extensive during the subsequent 50 years (Bebi et al. 2003, Kulakowski et al. 2003). As the weather during the 50 years following this outbreak was not particularly conducive to fire, it was hypothesized that outbreaks may have to be followed by drought for potential increase in fire risk to be realized. But even during the extreme drought of 1999–2002, the 1940s outbreak in the Flat Tops area of northwestern Colorado had only a minor influence on the behavior of the Big Fish Lake fire of 2002 (Bigler et al. 2005). This finding is consistent with the suggestion that increased flammability in subalpine forests of the southern Rockies may last only several years following outbreak, until fine fuels decay (Knight 1987, Bebi et al. 2003). After that time, the likelihood that an ignited fire may become extensive or severe may actually decrease for decades due to the decrease in fine fuels. Thus, it is in the years during and immediately following an outbreak that the risk of fire is expected to be highest. Any potential increase in fire risk that may have resulted from the 1940s outbreak in the Flat Tops may have declined in the ~60 years between that outbreak and the 2002 Big Fish Lake fire.

In addition to blowdowns and insect outbreaks, stand-replacing fires alter cover type and stand age, which may also affect subsequent fire behavior. Flammability of many forest types is believed to increase with increasing stand age (Loope and Gruell 1973). The effects of disturbance history, which successionally change with time since the disturbance, are expressed in both stand structure and tree species composition. Additionally, as a stand ages, tree mortality can increase the amount of dead fuels. Fire creates patches of different structure and composition and, in turn, fire spread and behavior are also influenced by these spatial patterns of fuel differences among stands of different ages across landscapes (Despain and Sellers 1977, Turner and Romme 1994, Minnich and Chou 1997). For example, the age of lodgepole pine stands in Yellowstone National Park is primarily determined by the time since the last severe fire (Romme 1982). In Yellowstone, Despain and Sellers (1977) found that fires became less severe or extinguished when they reached younger stands, which had a less flammable fuel complex. Similarly, in the Flat Tops area of Colorado, stands that burned in the late 19th century were less likely to burn during the 2002 fire than stands that had not burned at that time; and aspen stands, which were associated with the late 19th century postfire stands, were less likely to burn than other cover types (Bigler et al. 2005).

Fire spread across a landscape may be influenced by the juxtaposition of stands with different disturbance histories (Knight 1987). However, the strength of the influence of pre-burn stand conditions and landscape patterns is expected to decline with increasingly severe fire weather (Turner et al. 1994, Turner and Romme 1994). Furthermore, prefire vegetation conditions may not strongly affect fire behavior in all forest types. For example, the fire regime of subalpine forests in the Canadian Rocky Mountains has been shown to be more influenced by climate than by stand age or total fuel loads (Bessie and Johnson 1995).

Large infrequent stand-replacing fires that are associated with drought can create a coarse-scale mosaic of different age patches in the subalpine zone of the southern Rocky Mountains, which are composed of Engelmann spruce (*Picea engelmannii* (Parry) Engelm.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.), and quaking aspen (*Populus tremuloides* Michx.) forests (Romme and Knight 1981, Rebertus et al. 1992, Kipfmueller and Baker 2000, Veblen 2000, Kulakowski and Veblen 2002, Buechling and Baker 2004). Surface fires have been shown to burn only relatively small areas and do not have a major influence on stand structure (Kipfmueller and Baker 2000; Sibold et al. 2006). In some subalpine forests following stand-replacing fires, *Pinus contorta* and *Populus tremuloides* are successional to *Picea* and *Abies*, and these successional changes may significantly alter fuel configurations. Older (less than ~150 year old) spruce–fir forests typically have low branches that create fuel ladders whereas in relatively young (less than ~120 year old) lodgepole pine forests there are few branches near the ground surface (Despain and Sellers 1977). Aspen is well known to be less likely to burn than surrounding conifer stands, which may be due to lower flammability of this species as well as moister site conditions within aspen stands (van Wagner 1977). The successional replacement of aspen and lodgepole pine by spruce and fir may thereby contribute to age-related differences in fire potential.

In northwestern Colorado a major blowdown in 1997 followed by bark beetle outbreaks, salvage logging, and severe fires in 2002 provided a rare opportunity to examine disturbance interactions in the subalpine zone. In 1997 a windstorm with winds of 200–250 km/h blew down >10 000 ha of subalpine forest in the Routt Divide area of northwestern Colorado (Wesley et al. 1998, Baker et al. 2002). Following the blowdown, populations of spruce beetle colonized fallen trees, and the resulting broods began colonizing standing trees (Schaupp et al. 1999, 2002). Blowdowns can potentially trigger outbreaks of spruce beetle by providing sanctuary from cold winter temperatures and a food source for these beetles (Schmid and Frye 1977). At approximately the same time, mountain pine beetle (*Dendroctonus ponderosae* Hopkins) populations began attacking lodgepole pine in the study site, although most likely this was not as a result of the blowdown (Amman 1983). By 2002, >14 000 ha of forest were affected by spruce beetle and close to 1000 ha were affected by mountain pine beetle. In 1999, salvage logging operations began on parts of the blown down forest and by 2002, 808 ha were salvage logged in the study area. In 1999–2002, a severe drought affected Colorado with record low precipitation and Palmer Drought Severity Index values close to −6.0 (data *available online*).[2] In 2002, extensive and severe fires burned large areas of subalpine forest in this area.

Using spatial data sets on disturbance history and vegetation conditions, we examined the effects of the 1997 blowdown, recent bark beetle outbreaks, salvage logging, and fire history on the extent and severity of the 2002 fires. We hypothesized that the 2002 fires were more extensive and severe in (1) areas more severely affected by the 1997 blowdown; (2) areas affected by the 1998–2001 bark beetle outbreaks; (3) areas that were not salvage logged in 1998–2001; and (4) in older stands as opposed to young (<120 yr) postfire stands. Obviously, ignition point and weather during a fire event are important variables affecting fire spread, but these variables were not considered in the present study because our aim was to test the relationships of fire attributes to environmental variables that can be known prior to a fire event. Thus, our focus is on assessing susceptibility of a landscape to potential fire extent and severity rather than explaining fire pattern related to weather and ignition locations that cannot be ascertained a priori.

Study Area and Methods

Study area

The 84 497-ha study area is located in an area of northwestern Colorado that was affected by the severe 1997 blowdown. Ninety-nine percent of the study area is in Routt National Forest and the remainder is private land. The study area ranges from 2400 to 3400 meters (8000–11 000 feet) above sea level (Fig. 1). Forests are dominated by *Pinus contorta* Dougl. var. *latifolia* Engelm. (lodgepole pine), *Populus tremuloides* Michx. (quaking aspen), *Picea engelmannii* (Parry) Engelm. (Engelmann spruce), and *Abies lasiocarpa* (Hook.) Nutt. (subalpine fir). In the present study area, 7857 ha of forest were blown down, 808 ha were salvage logged, 14 155 ha were affected by spruce beetle outbreak, 883 ha were affected by mountain pine beetle, and 10 065 ha were burned in 2002. The remaining area was unaffected by these disturbances.

The study area has a continental climate with a mean annual temperature (calculated over 1910–1999) of 3.8°C that ranges from a mean monthly temperature of −9.6°C in January to 16.5°C in July (Colorado Climate Center, *available online*).[3] Mean annual precipitation (calculated over 1910–1999) is 60.5 cm and ranges from a mean monthly precipitation of 6.3 cm in January to 3.9 cm in July. Upland forest communities in this area are underlain by coarse-textured soils derived primarily from Precambrian crystalline rocks and glacial deposits, whereas soils in valley bottoms are typically derived from poorly drained alluvial deposits (Hoffman and Alexander 1980, Snyder et al. 1987).

Methods

Geographic information systems (GIS) and classification trees (Breiman et al. 1984) were used to model the extent and severity of the 2002 fires based on pre-2002 blowdown, outbreak of spruce beetle, outbreak of mountain pine beetle, salvage logging, topography, forest type, and forest structure. Spatially explicit data were compiled for the entire study area on these 1997–2002 variables and the 2002 fires. These data were entered into a GIS and subsampled with 3127 randomly located points that were used to model the extent and severity of the 2002 fires. Data on earlier stand-replacing fires were available for only a part of the study area and were therefore overlaid with the residuals of the model to test whether the effect of earlier fires helped to further explain the extent or severity of the 2002 fires after all other variables have been taken into account.

Data on forest type and stand structure were derived from the USDA Forest Service Resource Information System (RIS, USDA Forest Service 1998). Forest type data is indicative of tree species dominance of the canopy. Stand structural data is a measure of the percent of area covered by foliage above 1.4 m. Topography was derived from a 30-m digital elevation model. The extent and severity of the 1997 blowdown was mapped based on interpretation of 1:12 000 aerial photographs that were taken in 1997 after the blowdown and field verification of that interpretation (Baker et al. 2002). The numbers of fallen trees and trees left standing were tallied from photos and the percentage of trees blown down relative to the number of pre-blowdown trees was calculated for each patch of blowdown. The counts are primarily of larger trees in the canopy of the forest. Digital maps of the presence or absence of salvage logging and bark beetle outbreaks were created by the USDA Forest Service (*unpublished data*) and based on

[2] ⟨http://www.ncdc.noaa.gov/oa/climate/research/2002/may/sw0205.html⟩

[3] ⟨http://climate.atmos.colostate.edu⟩

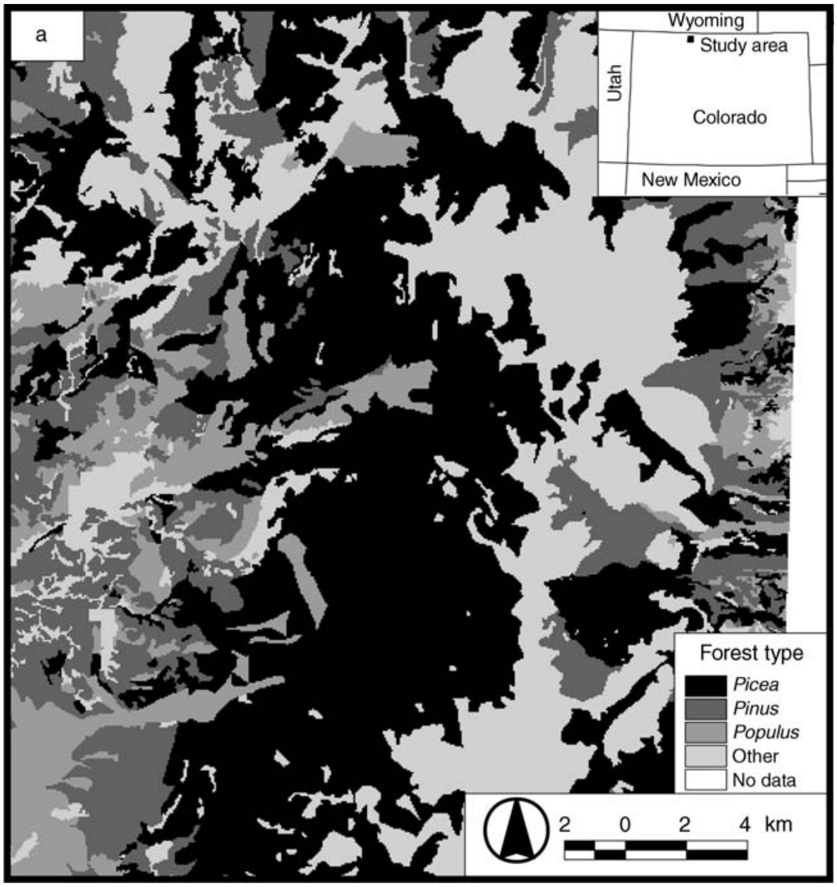

FIG. 1. (a) Location of the study area (inlaid) and forest cover type; (b) the extent and severity of the 1997 blowdown within the study area; (c) extent of spruce beetle outbreaks in 2002; (d) extent of mountain pine beetle outbreaks in 2002; and (e) extent of salvage logging 1997–2002.

aerial and field surveys. The most recent aerial surveys prior to the 2002 fires were conducted between 25 July and 2 August 2002. The history of stand-replacing fires prior to 2002 was reconstructed in a 4400-ha study area using a combination of aerial photograph interpretation and dendroecological methods (Kulakowski and Veblen 2002). This 4400-ha area consists primarily of postfire cohorts that established in 1879, ca. 1690, and ca. 1626, and old-growth forest. The extent and severity of the 2002 fires were derived by the USDA Forest Service from Landsat imagery from that year. Fire severity was based on the normalized difference burn ratio (NDBR), and the classification resulted in four categories of burn severity: fire severity 1, very low severity; fire severity 2, low severity (surface fire, overstory largely not scorched); fire severity 3, moderate severity (many canopy tree crowns scorched, some green crowns remained); fire severity 4, high severity (all canopy trees killed). The spatial and categorical accuracy of this data set was checked in the field at 36 sites that were selected using a stratified random design (D. Kulakowski and T. T. Veblen, *unpublished data*). All sites were correctly classified on the fire map.

The study area was subsampled in the Arc GIS (ESRI 2002) using randomly located points that were $>$500 m apart. Seventy-five percent of the points were used for model development (MD) and the other 25% were used for model validation (MV). In the statistical package S-Plus (MathSoft 1999), classification trees were used to describe the relationship between the extent (occurrence) and severity of the 2002 fire and prefire conditions. The tree model is fitted using binary recursive partitioning whereby the data are successively split along coordinate axes of the predictor variables so that at any node the split is selected that maximally distinguishes the response variable in the left and the right branches. Classification trees are ideally suited for the analysis of complex ecological data due to their ability to robustly analyze nonlinear relationships, high-order interactions, and missing values and to provide easily interpretable results (De'ath and Fabricius 2000). Fire extent (burn classes $>$ 1) and fire severity (burn classes 1–2 vs. 3–4 within a known perimeter) were analyzed separately. Independent variables included percentage blowdown, occurrence of salvage logging, mortality caused by spruce beetle, mortality caused by mountain pine beetle,

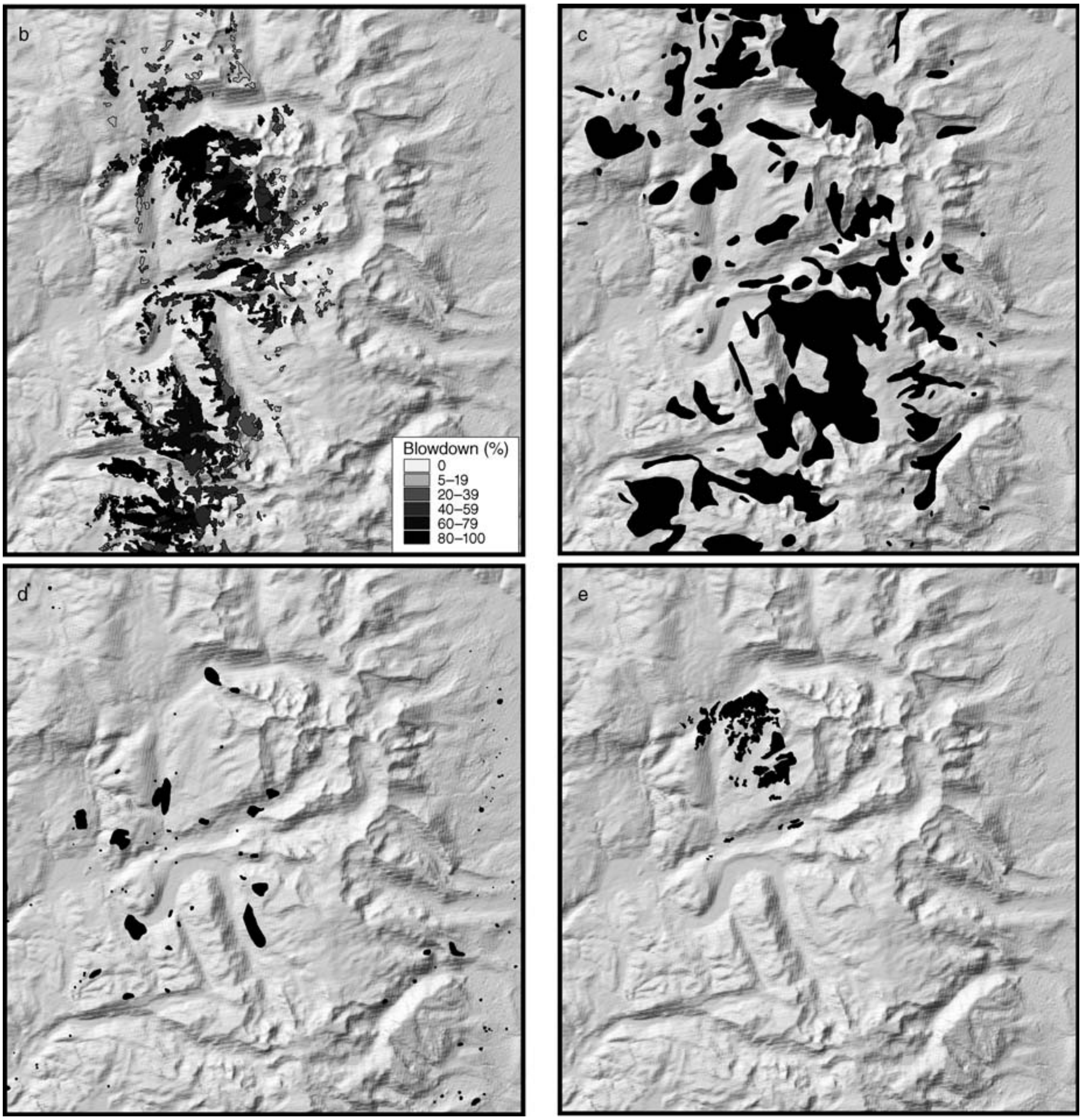

FIG. 1. Continued.

forest cover type, percent crown cover, slope steepness, elevation, and aspect (southerly vs. northerly). Classification trees were pruned based on cost complexity, a standard approach to fitting tree models. Cost complexity pruning determines a nested sequence of subtrees by recursively "snipping" off the least important splits. The classification tree models were used to make spatial predictions of fire extent and fire severity using the StatMod extension for statistical modeling in Arc (C. M. Garrard, *available online*).[4] Models of fire severity were evaluated by Cohen's kappa (Cohen 1960). Kappa measures the proportion of all possible cases of presence or absence that are predicted correctly by a model after accounting for chance and is a robust indicator of model performance (Manel et al. 2001). Values of kappa range from <0 (agreement between model and empirical data is not greater than that which is expected to occur by chance) to 1 (complete agreement between model and empirical data). In addition to kappa, models of fire severity and extent were evaluated by comparing misclassification rates between the model and the majority rule, as is standard for classification trees (De'ath and Fabricius 2000). Moran's I was used to measure spatial autocorrelation of model residuals.

4 ⟨http://arcscripts.esri.com/details.asp?dbid=12502⟩

Because dates of last stand-replacing fires prior to 2002 were reconstructed for only 4400 ha of the 84 497-ha study area, this independent variable could not be used for the analysis of the entire area. Instead, residuals of the classification tree models developed for the large study area were laid over polygon coverage of the last stand-replacing fire in the 4400-ha study area. Observed rates of Type II errors (burned or severely burned, but not predicted as such) in each class of the last stand-replacing fire were compared to predicted rates of these errors. Overlay analysis tabulates the total area of all values of one variable that occur in each value of a second variable. The observed amount was compared to the expected amount of this error for each category, which is proportional to the amount of total area in that category. If the date of the last stand-replacing fire does not influence the presence of unexplained burning, then the amount of Type II error in each class of fire history is expected to be proportional to the amount of Type II error in the whole 4400-ha study area. Thus, a positive departure of the observed from the expected is indicative of greater susceptibility to fire whereas a negative departure indicates resistance to fire.

Results

Prefire conditions, which included cover type, topography, blowdown, bark beetle outbreaks, and salvage logging were poor predictors of fire extent. Cover type was the most important variable in predicting fire extent such that spruce–fir stands were more likely to have burned than expected and aspen, lodgepole pine, and other stands were more likely not to have burned than expected (Fig. 2a). Blowdown and elevation were of secondary importance. Salvage logging and mortality caused by bark beetle outbreak had no detectable effect on fire extent. This model poorly described fire extent (Fig. 3a, b). The model misclassification rate was 9.3% vs. the majority misclassification rate of 14.1%, thus the model reduced misclassification by only 4.8%. Spatial autocorrelation was high (Moran's $I > 0.5$) among residuals at distances <438 m and was significant ($P < 0.05$) at all distances at which it was measured (≤1500 m).

In contrast, prefire conditions were good predictors of fire severity within a given fire perimeter. Blowdown was the most important predictor of the occurrence of high-severity fire (Fig. 2b). Within the fire perimeter, 90% of stands that experienced severe (>66.1%) blowdown burned severely in 2002. In contrast, only 34% of stands that were not severely blown down burned severely. Crown cover (percentage closure) and elevation were of secondary importance. Among stands that were less severely blown down, stands with dense crown cover (>82.5%) were more likely to burn severely. Among stands that were more severely blown down, stands <3153 m were more likely to burn severely. Salvage logging and mortality caused by bark beetle outbreak had no detectable effect on fire severity. This model predicted fire severity with high accuracy (Fig. 3c, d). The model misclassification rate was 13.5% vs. the majority misclassification rate of 44.7%, thus the model reduced misclassification by 31.2%. Kappa values of 0.63 (SE = 0.0449; z score = 14.0432) for MD and 0.39 (SE = 0.0449; z score = 8.58044) for MV were likewise very good. Spatial autocorrelation was high (Moran's $I >$ 0.5) among residuals at distances <233 m and was significant ($P < 0.05$) at distances ≤1000 m. The spatial autocorrelation was higher and significant at greater distances among residuals of the fire extent model than of the fire severity model. This indicates that fire extent is a much more spatially determined process as opposed to fire severity, which is more substantially influenced by prefire site conditions.

The history of earlier stand-replacing fires affected the extent and severity of the 2002 fires in the 4400-ha study area for which dates of the last stand-replacing fires were reconstructed (Fig. 4). Areas of Type II errors (burned or severely burned, but not predicted as such) occurred less than expected in young (~120 year old) postfire stands. These stands were less likely than expected to have been either burned (71% less than expected) or burned severely (58% less than expected). In contrast, areas of Type II errors (burned or severely burned, but not predicted as such) occurred more than expected in old (~300–400 year old) postfire stands and old-growth stands (more than ~400 year old).

Discussion

Prefire conditions, with the notable exception of the time since the last stand-replacing fire, had little detectable influence on fire extent. Previous work in nearby subalpine forests has generally indicated that the occurrence of large fires in such relatively mesic ecosystems is limited primarily by the occurrence of drought rather than by fuel accumulation (Kipfmueller and Baker 2000, Buechling and Baker 2004; Sibold et al. 2006). Dry conditions, especially when combined with wind, are necessary and sufficient for fire to spread over large areas in subalpine forests. Changes in fuels, even such as those brought about by a severe blowdown, appear to have little effect on fire extent during drought. An implication of this is that without a priori knowledge of the point of ignition and weather during the fire (which are impossible to ascertain), it may not be possible to accurately predict the extent of fires in these subalpine forests based on the spatial distribution of blowdown or bark beetle outbreak.

We found no evidence that the bark beetle outbreaks following the 1997 blowdown influenced either fire severity or extent. Previous work in Colorado subalpine forests showed that there was no increase in fire frequency or extent as a result of the 1940 spruce beetle outbreak in the Flat Tops area of northwestern Colorado during the subsequent 50 years, which was a time period lacking severe drought (Bebi et al. 2003, Kulakowski et al. 2003). When forests affected by this beetle outbreak were burned in the Big Fish Lake fire during the extreme drought of 2002, the 1940s outbreak had only a relatively

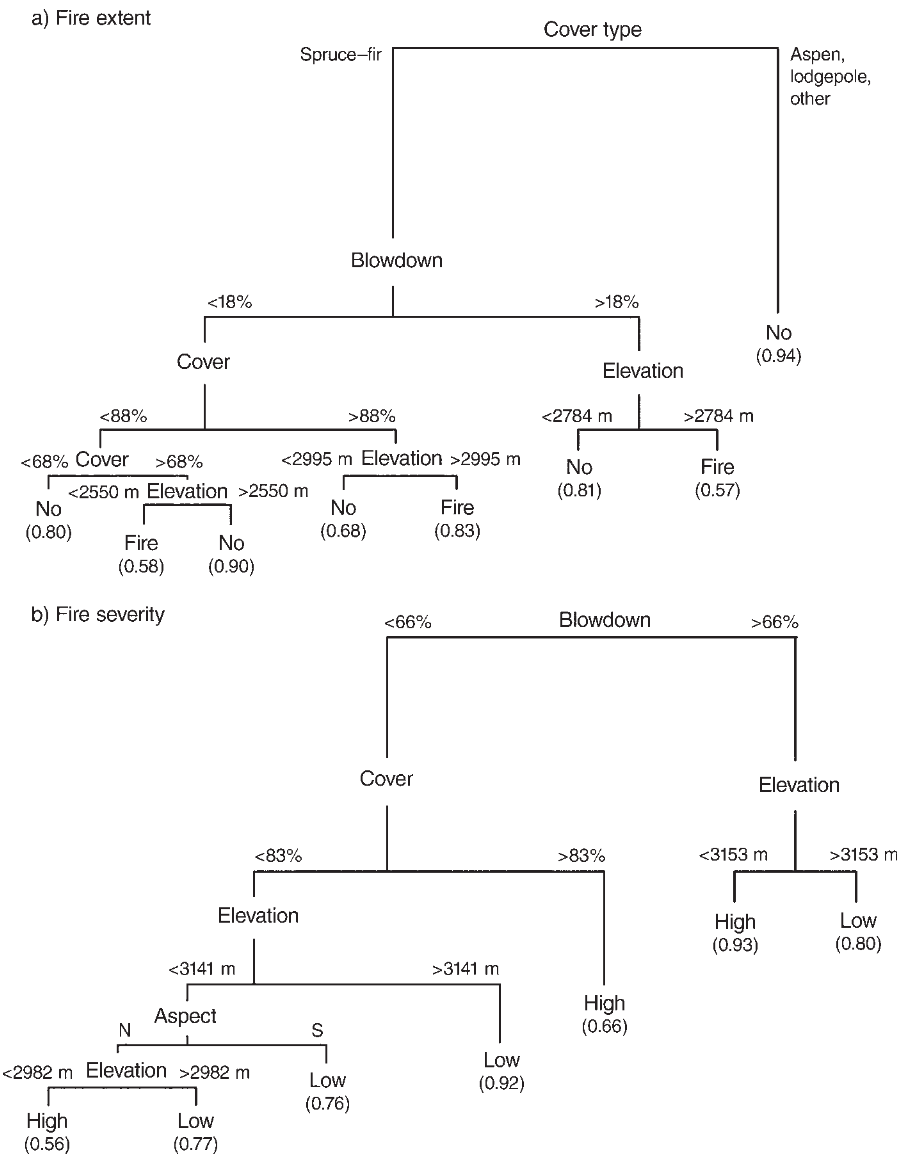

FIG. 2. Classification trees of (a) fire extent (normalized difference burn ratio [NDBR] values >1). The model misclassification rate was 9.3% vs. the majority misclass of 13.4%. (b) Fire severity (high NDBR values $\geq$3 vs. low NDBR values <3). The model misclassification rate was 13.5% vs. the majority misclass of 44.7%, $\text{kappa}_{\text{MD}} = 0.63$ (MD, model development; SE = 0.0449; *z* score = 14.0432), $\text{kappa}_{\text{MV}} = 0.39$ (MV, model validation, SE = 0.0449; *z* score = 8.58044). The length of horizontal lines is proportional to the explained variance. Each terminal node is labeled according to the predominant classification of (a) fire occurrence (fire or no fire) or (b) severity (low or high). Parenthetical numbers indicate the probability of that classification. The figure depicts trees trimmed to 10 terminal nodes. Complete trees were pruned based on the cost-complexity measure and included 133 terminal nodes for fire extent and 55 terminal nodes for fire severity.

minor influence on fire behavior (Bigler et al. 2005). Although the coarse dead fuels were still present in 2002, the fine dead fuels created by this outbreak decomposed over the ~60 years between the outbreak and the 2002 Big Fish Lake fire. Indeed it has been postulated that any increase in fire hazard as a result of a bark beetle outbreak may need to coincide with extreme drought during the several years following the outbreak, and prior to the decomposition of fine fuels, in order for the increased fire potential to be realized (Knight 1987, Bebi et al. 2003). In the present study area, the extreme drought of 2002 occurred several years after the beginning of the current outbreaks of spruce beetle and mountain pine beetle, at a time when dead fine fuels were still on recently killed trees. Thus in the present study we examined the previously unaddressed question of how a fire that occurs only a few years after the beginning of bark beetle outbreaks affects fire extent and severity. Even during such optimal conditions of availability of dead fine fuels, the occurrence of bark beetle outbreaks

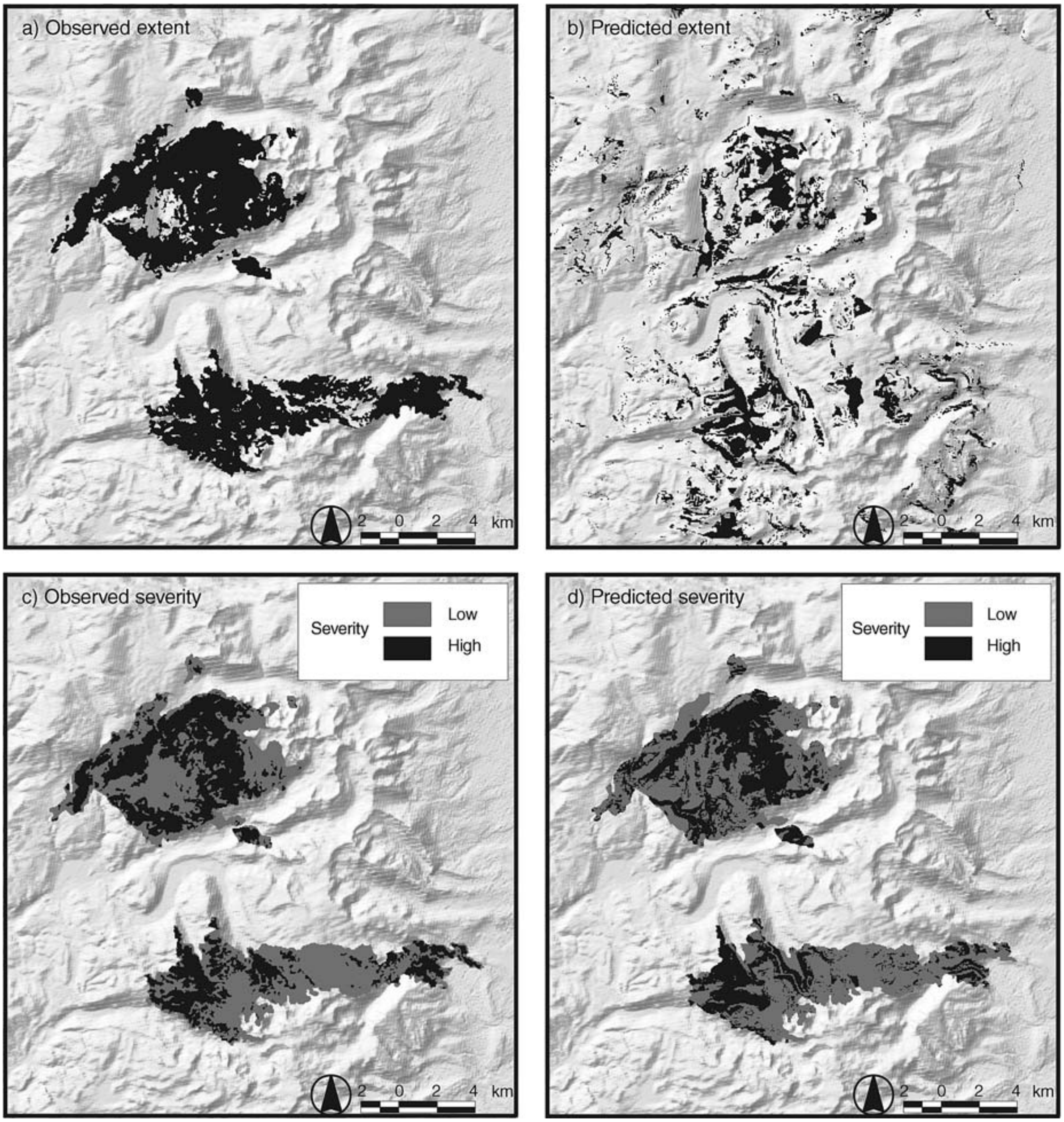

FIG. 3. Maps of (a) observed fire extent (normalized difference burn ratio; NDBR values >1), (b) predicted fire extent, (c) observed high (NDBR values ≥ 3) and low (NDBR values <3) fire severity, and (d) predicted high and low fire severity. Predicted values were calculated for each 30-m grid cell based on classification trees that were trimmed using the cost-complexity measure (see Fig. 2).

did not appear to affect either fire extent or severity. Changes in fuels brought about by outbreaks do not appear to have a major influence on fire extent or severity in these subalpine forests, even in the years during and immediately following the outbreaks. However, we caution that inherent limitations in the data sets used in the present study may influence this interpretation. The identification of stands affected by outbreak is based largely on aerial surveys, which rely on visual detection of killed trees. The variable delay between the time the tree is killed and the time the needles are discolored leads to a corresponding delay in detection of the outbreak. Thus it is likely that the area affected by outbreak was more extensive prior to the 2002 fires than our data indicate. This discrepancy may affect our ability to detect the influence of outbreak on the 2002 fires. Therefore, the lack of relationship between outbreak and the 2002 fires in the present study area should be interpreted cautiously. More studies of the effects of bark beetle outbreaks on fire extent and severity are needed. Such future studies could benefit from improved methods, possibly combining remote sensing with ground surveys, of detecting the true extent of recent and ongoing outbreaks.

Even though salvage logging following disturbances such as blowdown is sometimes intended to reduce fire risk, we found no evidence that salvage logging following the 1997 blowdown influenced either fire extent or severity. The salvage logging primarily removed large timber and, although small fire breaks are created by roads and destruction of the regeneration that survived the initial blowdown, these operations apparently left enough slash (i.e., branches and other residue left on a forest floor after the cutting of timber) so that fire extent and severity during extreme drought were not significantly affected. The present work implies that mitigation efforts such as salvage logging following blowdown do not always reduce the likelihood of extensive and severe fires. This is especially true in forest such as those in the subalpine zone of the Rocky Mountains, in which fires may be primarily limited by weather (i.e., extreme drought) as opposed to fuels. Similarly, logging following the 2002 Biscuit Fire in Oregon actually increased fine and coarse fuels and thus inadvertently increased fire risk (Donato et al. 2006). However, the effect of salvage logging on the behavior of severe fires is likely to vary depending on whether or not slash is removed and on the extent of the logging. Although current salvage logging practices may influence fire behavior during years with average precipitation, these practices appear not to be effective at influencing either fire extent or severity during extreme drought, and it is during these extremely dry conditions that fires typically occur in these ecosystems.

Stand-replacing fires arguably exert the greatest change and leave the longest legacies of any type of disturbance that is known to affect the subalpine forests of the southern Rockies (avalanches, insect outbreaks, wind disturbances). These legacies have been shown to affect the behavior of subsequent fires in Yellowstone (Romme 1982) and elsewhere (Krawchuk et al. 2006). We also found that time since the last stand-replacing fire prior to 2002 helped to explain the extent and severity of the 2002 fires. In the 4400-ha study area for which fire history was reconstructed prior to 2002, stands more recently affected by stand-replacing fires (i.e., in the late 19th century) were affected less extensively and less severely than older stands. In the 2002 fires in the Flat Tops area of Colorado, the occurrence of late 19th century fires was also one of the most important factors that affected fire severity such that stands that established following fires in the late 19th century were less likely to burn than older stands (Bigler et al. 2005). While changes in fuels such as those brought about by blowdown, outbreak, and logging have a negligible influence on fire extent, the much larger differences in fuels that result from stand-replacing fires are important in determining the extent and severity of subsequent fires. Stand-replacing fires result in a substantial reduction of both fine and coarse fuels for decades. This reduction

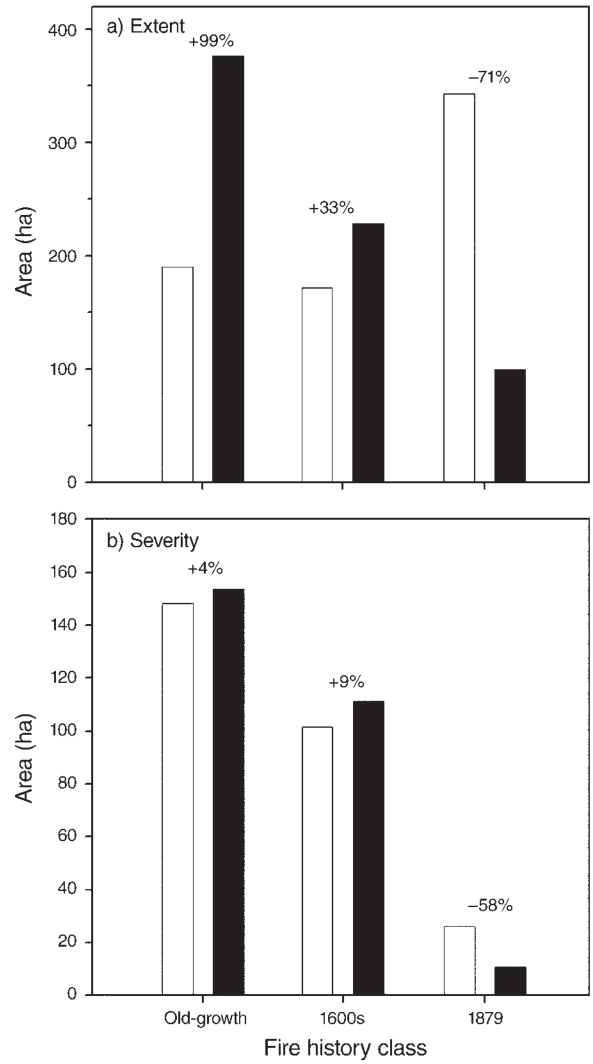

FIG. 4. Observed (solid bars) and expected (assuming no effect of fire history; open bars) occurrence of Type 2 model residuals (burned or burned severely but not predicted as such) of (a) fire extent and (b) fire severity in areas of different fire history. Young postfire stands established in 1879 and old postfire stands established ca. 1626–1690. "Old-growth" forests are defined here as those that have not been affected by a stand-replacing disturbance for more than ~400 years (Kulakowski and Veblen 2002). Numbers above bars indicate percentage departure of observed from expected.

reduces forest susceptibility to extensive or severe fires. Thus it is likely that the areas that burned in 2002 will be more resistant to fire for the next >100 years. Previous work has found that young postfire stands in Colorado are also more resistant to bark beetle outbreak and blowdown than older stands (Veblen et al. 1994, Kulakowski and Veblen 2002, Bebi et al. 2003, Kulakowski et al. 2003). Thus stand-replacing fires give rise to young stands that are less susceptible to most major types of disturbances. Furthermore, while fires such as those in the late 19th century and in 2002 can be considered large at a stand scale, they affect only a fraction of the entire landscape, and thus increase heterogeneity of vegetation at the landscape scale. This heterogeneity plays an important role in determining the subsequent disturbance regime and in effect buffers the landscape against large, severe disturbance events.

Although natural disturbances do affect fuel characteristics, the actual effect of these disturbances on fire behavior can be complex, especially in more mesic forests within which the occurrence of extensive severe fires largely depends on extreme drought as opposed to fuel accumulation. The results of the present study imply that within such ecosystems fire extent and severity are controlled by different variables. Specifically, fire extent is largely independent of prefire vegetation conditions such as recent history of blowdown and bark beetle outbreak and is more likely to be influenced by drought, point of ignition, and weather during the fire event. Similarly, the extent of the 2002 Hayman Fire in Colorado was largely determined by weather during that fire (Finney et al. 2003).

In contrast to fire extent, fire severity, even during extreme drought, is strongly tied to prefire conditions especially the effect of previous disturbance by blowdown. Although the strength of the influence of prefire stand conditions and landscape patterns on fire behavior is expected to diminish with increasingly severe fire weather (Turner et al. 1994, Turner and Romme 1994), the current study showed that even during severe drought blowdown affected fire severity. Blowdown was the most important variable in determining fire severity and the performance of this model was very good based on values of kappa. The increased fire severity following blowdown was probably due to a combination of drier fuels among the trees that were killed in the blowdown and the greater likelihood of flames reaching the crowns of fallen trees. This is consistent with the idea that compounding disturbances that occur in short succession, before the ecosystem has had a chance to recover from the initial disturbance, can have a greater effect on the ecosystem than the same two disturbances further separated in time (Paine et al. 1998). While many tree species may be well adapted to resist or recover from individual natural disturbances, compounded disturbances can increase disturbance severity so that subsequent ecosystem recovery is delayed or altered in trajectory.

Disturbance extent and severity are two separate components of disturbance regimes and have different causes and ecological effects (Malanson 1984, White and Pickett 1985, White and Jentsch 2001). The present work indicates that prefire disturbances have different relative influences on fire extent and fire severity and that different factors are responsible for these two components of the same disturbance. The extent of the area affected by the 2002 fires in the present study was not strongly influenced by prefire cover type, topography, blowdown, bark beetle outbreak, or salvage logging, but was influenced by the time since the last stand-replacing fire. In contrast, the severity with which the fires affected the ecosystem was strongly tied to prefire conditions, especially to blowdown and the time since the last stand-replacing fire.

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